IJE TRANSACTIONS B: Applications Vol. 27, No. 11, (November 2014) 1757-1766

International Journal of Engineering

Journal Homepage: www.ije.ir

Controlling the Power Output and Combustion Phasing in an Homogeneous Charge Compression Ignition Engine

M. Nazoktabar*, S. A. Jazayeri

Mechanical Engineering Department, K.N. Toosi University of Technology, Tehran, Iran

PAPER INFO

Paper history:
Received 15 May 2014
Received in revised form 16 June 2014
Accepted 26 June 2014

Keywords:
HCCI Engine Control
Two Input Two Output Controller
Fuel Rate & Phi Inputs
IMEP & CA50 Outputs

ABSTRACT

In the development of Homogeneous Charge Compression Ignition (HCCI) engines, simultaneous control of combustion phasing and power output has been a major challenge. In this study, a new strategy is developed to control the engine power output and combustion phasing at any desired operating condition. A single zone thermodynamic model coupled to a full kinetic mechanism of Primary Reference Fuels (PRFs) is developed to predict characteristic parameters such as; Start of Combustion (SOC) and Indicated Mean Effective Pressure (IMEP) and also thermodynamic constant parameters for processes through an HCCI engine cycle. A dynamic interactive control model has been developed for the entire cycle of a HCCI engine to predict combustion phasing and IMEP.The results derived from the developed model are validated against experimental data for a single cylinder Ricardo engine. A two input - two output controller is then designed to track crank angle at which 50% of in cylinder fuel mass is burned (CA50) and IMEP by adjusting the input data. In this study two control models are presented; open loop and closed loop. Performance of the controller is tested on a physical HCCI engine model to evaluate the tracking performance and disturbance rejection properties. Results indicate that the designed controller is capable to accurately tracking both CA50 and IMEP while rejecting the disturbances from variations in the engine speed and the intake manifold temperature.

***doi**: 10.5829/idosi.ije.2014.27.11b.14*

1. INTRODUCTION

Most of the investigations in conventional engines are finding new strategies for reduction of emissions and enhancement of their performance [1, 2]. It is well known that Homogeneous Charge Compression Ignition (HCCI) engines have benefits of both Otto and diesel cycles. Possibility of having ultra lean mixture and lower combustion temperature together with no throttling losses could give a great advantage for reduced Nitrogen Oxides (NOx) and particulate matter emissions while increasing the efficiency compared with conventional internal combustion engines [3]. A major advantage of HCCI combustion is its flexibility to work with a variety of fuels. Reduction in availability and increased price of fossil fuels on one hand, and more strict legislations for engine emission levels result in increased interest in application of HCCI engines. However, application of HCCI engines are accompanied with some drawbacks such as limited operating range and higher unburned hydrocarbon and carbon monoxide emissions. High sensitivity of HCCI combustion to mixture properties and physical occurrence within cylinder significantly make the HCCI control more complex. This can drastically affect the power output and also control of combustion phasing [4, 5]. As a result, HCCI engines have a limited range of operation in terms of engine speed and power while there are more complexities for accurate control of combustion phasing.

There is a major challenge to control the initiation of combustion in a HCCI engine under various operating conditions. The Ignition timing could easily affect performance, emissions, operating range and combustion stability [6]. To control initiation of combustion in an HCCI engine, one strategy is to control the charge properties during intake and compression stroke. These are several accepted methods: changing the amount of residual gas trapped in

*Corresponding Author's Email: Nazoktabar@riau.ac.ir (M. Nazoktabar)

Please cite this article as: M. Nazoktabar, S.A. Jazayeri, Controlling the Power Output and Combustion Phasing in an HCCI Engine, International Journal of Engineering (IJE), TRANSACTIONS B: Applications Vol. 27, No. 11, (November 2014) 1757-1766

the engine cylinder [7], variation of charge temperature in intake manifold by a thermal management system [8], changing effective compression ratio by means of variable valve timing or actuation systems [7, 9], changing fuel octane number (ON) [10, 11] and changing fuel injection timing [12, 13]. More studies are carried out to control the combustion phasing in HCCI engine and certain work to control the engine via work output or IMEP [9, 14]. In previous work, ϕ is used as the main input to control IMEP in an HCCI engine. Since phi is a qualitative parameter then in order to control IMEP some quantitative parameters such as air and fuel mass flow rate should be considered. In a four stroke engine power could be presented as [15]:

$$P = \frac{(\eta_f \eta_v \rho_a) N V_d Q_{HV} (F/A)}{2} \tag{1}$$

The above equation contains influential parameters on engine power output. For a specific engine under specified operating conditions of η_f, η_v and ρ_a are constant. But, NV_d, Q_{HV} and F/A represent the Air Flow Rate (AFR), Fuel Flow Rate (FFR) and equivalence ratio, respectively. It is obvious that the AFR and FFR are more effective than equivalence ratio. On the other hand, in conventional engines in order to control the engine power, Initially in CI engine fuel rate and in SI engine AFR are changed. But, in order to control HCCI engine output power more consistently, FFR and AFR should be adjusted at the same time as the inputs. In HCCI engine, control of combustion phasing is much more challenging. When there is a demand to change IMEP, to control combustion timing an appropriate phi as second input is selected from CA50-phi map after that phi is adjusted according to the desired combustion timing.

The CA50 is controlled in a HCCI engine for any required output work. In fact HCCI engine control system should be conducted through a load-speed map. In a conventional engine, the throttle and fuel rate are two variables that are changed according to desired power or torque demand. In this study for HCCI engine, optimal IMEP is considered the main parameter to be controlled by a proper CA50.

2. CONTROL MODEL DESIGN

A control model is developed to predict cycle-to-cycle variation of IMEP and CA50 in an HCCI engine. In order to simulate the behavior of HCCI engine cycles a physics-based Control Oriented Model (COM) is developed. Also, a single zone thermodynamic model is developed to determine thermodynamic constants and predict parameters such as: SOC and IMEP.

2. 1. Single Zone Thermodynamic Model

Investigations [16-18] show that single zone thermodynamic model is fully capable of predicting the effects of combustion parameters to study HCCI engine behavior. In present work, a single zone thermodynamic model has been developed to determine the thermodynamic constant parameters in various processes of the engine cycle. By means of the model, the effects of some parameters such as inlet temperature and pressure, equivalence ratio, ON and engine speed on SOC and IMEP have been investigated. This model has been coupled to a full kinetic mechanism of PRFs[1]. In order to use the full kinetic mechanism of PRFs an open source module known as CANTERA has been coupled to the model. The chemical kinetics mechanism with 7558 reactions and 1034 species has been used to simulate the combustion process. Considering the arbitrary elementary reaction stated as follows:

$$\sum_{i=1}^{N} \upsilon'_{i,j} M_j \Leftrightarrow \sum_{i=1}^{N} \upsilon''_{i,j} M_j \quad j=1, 2, \ldots, N_R \tag{2}$$

Where M_j is the specie of j^{th} reaction, $\upsilon'_{i,j}$ and $\upsilon''_{i,j}$ are the stoichiometric coefficient of i^{th} specie on the product and reactant side of the j^{th} chemical reaction, respectively. The rate of change of each chemical species is described with an ordinary differential equation of the form:

$$\dot{\omega} = \sum_{i=1}^{N_R} RR_j \left(\upsilon'_{i,j} - \upsilon''_{i,j}\right) \tag{3}$$

$$RR_j = k_{f,j} \prod_{i=1}^{N_S} [M_i]^{\upsilon'_{i,j}} - k_{b,j} \prod_{i=1}^{N_S} [M_i]^{\upsilon''_{i,j}} \tag{4}$$

where $k_{f,j}$ and $k_{b,j}$ are forward and reversed j^{th} reaction rate, respectively. The model is validated with a large number of experimental data taken from Ricardo engine with specifications listed in Table 1.

For validation purposes in Figure 1 a sample pressure history derived from developed model is compared with test results extracted from reference [16]. The simulated and test data are in good agreement. Higher peak pressure than that of experimental data is due to the single zone model assumptions [5]. Experimental results and sensitivity analyses show that ϕ, ON and T_{ivc} are dominant parameters affecting the HCCI combustion phasing [6, 16]. In present study effects of engine speed, ϕ, ON, T_{ivc} and also engine speed has been investigated and it shows that the single zone model is capable of accurately predicting SOC in HCCI engine.

[1] www.pls.llnl.gov/data/docs/ science_and_technology /chemistry/ combustion / prf_2d_mech.txt

Figure 2 shows a sample of variations of SOC versus engine speed for different charge temperatures. Results highlights that the SOC is drastically affected by engine speed.

TABLE 1. Single cylinder Ricardo engine specifications

Parameter	Value
Bore	80 mm
Stroke	88.90 mm
Compression ratio	10:1
Displacement volume	0.447 Lit
Number of valves	4
IVO, IVC [aBDC]	-175/+55
EVO, EVC [aBDC]	-70/-175

TABLE 2. Values of the COM's constant parameters

Parameter	Value
$C_{v,nc}$	0.783 kJ/kgK
$C_{v,rg}$	0.814 kJ/kgK
R_{evc}	0.289 kJ/kgK
k_c	1.357 [-]
k_e	1.265 [-]

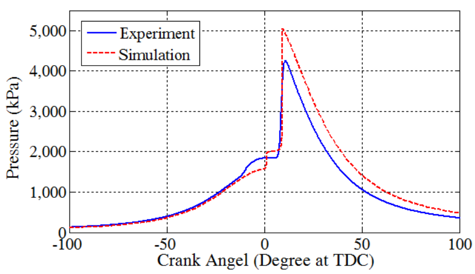

Figure 1. Comparison of simulated and experimental pressure measured in operating conditions P_{ivc}=105kPa, T_i =79 C°, EGR=6%, ϕ =0.67, N=800rpm and PRF=10.

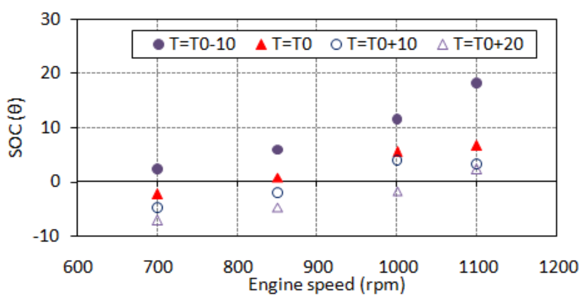

Figure 2. Variations of SOC versus engine speed for 4 inlet charge temperatures ($T_0 = 105C^{\circ}$)

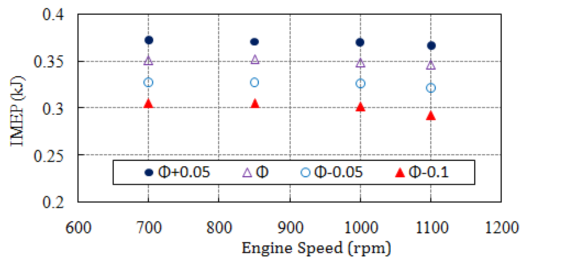

Figure 3. Variations of IMEP versus engine speed for 4 inlet equivalence ratio

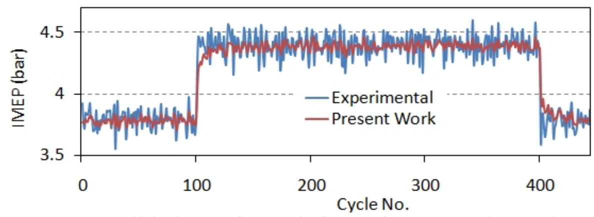

Figure 4. Validations of correlation 3 for a step change in ϕ and ON (P_{man} = 110 kPa, T_{man} = 91 °C, EGR= 0%, P_{exh} = 99 kPa , N= 815 rpm, Cycle No=445)

A correlation for predicting θ_{soc} is obtained through the simulation data and the Modified Knock Integral Method (MKIM) integral can be replaced by the mentioned correlation.

$$\theta_{soc} = \frac{0.23\times N}{(T_{ivc}^{\;0.43}\times\phi^{0.1})} + 0.06\times ON^{1.3} - 17.3 \tag{5}$$

The engine power output can be represented by IMEP and depends on both AFR and FFR. The thermo-kinetic model is used to determine the relationship between IMEP and dominant parameters that affect it considerably. A correlation between IMEP and relevant effective parameters are derived using a single-zone thermodynamic model for a complete HCCI engine cycle.

Figure 3 shows a sample of variations of IMEP with engine speed. According to this figure engine speed has less effect on IMEP but ϕ fluctuation would affect it considerably. This procedure has been done to investigate the effects of other dominant parameters on IMEP. Correlation (6) predicts IMEP of Ricardo engine for specified operation conditions.

$$IMEP = (FR)^{0.9}(0.132\Phi \,.\, T_{man} - 28.3\Phi + 6.43) \tag{6}$$

In derived correlation the effects of FFR, ϕ and CA50 has been considered. Using FFR and phi at the same time, AFR effect on IMEP is considered as well. The above correlation can predict the IMEP of a HCCI engine with high accuracy.

Correlation 6 is validated against the experimental data collected from the Ricardo engine for both steady state and transient operating conditions [19].

Figure 4 shows comparison of the predicted and experimental IMEP for step changes in the ϕ and ON in transient operating conditions. As mentioned before, present model is able to calculate the thermodynamic constant parameters such as gas constant, specific heat capacity and specific heat capacity ratio. They are calculated for the processes of COM cycle. Values of constant parameters are shown in Table 2.

2. 2. HCCI Model For a single cylinder Ricardo engine specified in Table 1, a simple open cycle simulation is carried out using physics based relations and governing equations for various processes from Intake Valve Closing (IVC) to Exhaust Valve Opening (EVO).

2. 2. 1. Assumptions The system inputs are:

- Equivalence ratio (phi) and fuel flow rate (FR).

The system outputs are;

- IMEP and CA50.

The following physical state variables are considered for HCCI engine modeling through a complete cycle:

- CA50
- Temperature at SOC
- Pressure at SOC
- Temperature of the residual gases at EVC
- IMEP

Since the residual gasses for engine cylinder within a cycle are mixed with the fresh charge of the next cycle and this would affect temperature at the IVC, then would influence combustion phasing together with IMEP of the next engine cycle.

2. 2. 2. Thermodynamic States of Cycle Processes

- *Intake stroke thermodynamic states*

Intake charge specification would directly affect the combustion timing so any physical-based model should contain all influential parameters. Temperature and pressure of the mixture could be derived using following empirical correlations [11].

$$P_{ivc,k+1} = \left(\frac{N_k^{C_1}\phi_k^{C_2}}{T_{man,k}^{C_3}}\right) P_{man,k} \tag{7}$$

$$T_{ivc,k+1} = (aT^2_{man,k} + T_{man,k} + C)\frac{N_k^e \phi_k^f}{(1+EGR)^g} \tag{8}$$

Also, the temperature increases due to trapped residual gas mixing with fresh charge;

$$T_{mix,k+1} = (1 - RGF_k)\frac{C_{v,nc}}{C_{v,t}} T_{ivc,k+1} + RGF_k \frac{C_{v,rg}}{C_{v,t}} T_{r,k} \tag{9}$$

- *Prediction of combustion phasing*

As mentioned before, the MKIM integral can be replaced by correlation (5) then, θ_{soc} of present cycle is calculated by dominant parameters of previous cycle.

$$\theta_{soc,k+1} = \frac{C_1 \times N_k}{(T_{ivc,k+1}^{0.43} \times \phi_k^{0.1})} + C_2 \times ON_k^{1.3} + C_3 \tag{10}$$

The CA50 could be calculated by;

$$CA50_{k+1} = \theta_{soc,k+1} + 0.5\Delta\theta_{comb,k+1} \tag{11}$$

- *Thermodynamic State of SOC*

At the start of combustion there are no changes in chemical composition of the mixture, so compression stroke is assumed to be isentropic process [15]. Therefore, temperature and pressure of the mixture is predicted by a polytropic relation $PV^{k_c} = const.$ where, k_c is the specific heat capacity ratio.

$$T_{soc,k+1} = T_{mix,k+1}(V_{ivc}/V_{soc,k+1})^{k_C - 1} \tag{12}$$

$$P_{soc,k+1} = P_{mix,k+1}(V_{ivc}/V_{soc,k+1})^{k_C} \tag{13}$$

where V_{ivc} and V_{soc} are in cylinder volumes at θ_{ivc} and θ_{soc} respectively, which is determined easily by a slider crank mechanism [15].

- *Thermodynamic State of EOC*

In cylinder gas temperature during combustion process is [14]:

$$T_{eoc,k+1} = T_{soc,k+1} + \Delta T_{comb} \tag{14}$$

$$\Delta T_{comb} = \frac{LHV_{fuel} \times \overline{CoC}}{(1+RGF_k)(AFR_{st}/\phi_k)\overline{C}_v} \tag{15}$$

where AFR_{st} and $\overline{CoC}$ are the stoichiometric air-fuel ratio and the average completeness of combustion respectively, and LHV_{fuel} is the lower heating value of PRFs. Pressure at the end of combustion using ideal gas law:

$$P_{eoc,k+1} = P_{soc,k+1}\left(\frac{V_{soc,k+1}}{V_{eoc,k+1}}\right)\left(\frac{T_{eoc,k+1}}{T_{soc,k+1}}\right) \tag{16}$$

- *Expansion Stroke*

The expansion of burned mixture is assumed adiabatic isentropic processes where $n = k_e$ related to specific heat capacity is:

$$T_{evo,k+1} = T_{eoc,k+1}\left(\frac{V_{eoc,k+1}}{V_{evo}}\right)^{ke-1} \tag{17}$$

$$P_{evo,k+1} = P_{eoc,k+1}\left(\frac{V_{eoc,k+1}}{V_{evo}}\right)^{ke} \tag{18}$$

- *Exhaust Stroke*

Isentropic relation determines the residual gas temperature at EVO:

$$T_{r,k+1} = T_{evo,k+1}\left(\frac{V_{evo,k+1}}{V_{evc}}\right)^{ke-1} \tag{19}$$

- *Prediction of IMEP*

Similar to Equation (3), IMEP of present cycle is calculated by relevant parameters of the previous cycle.

$$IMEP_{k+1} = FR_k^{C_4}\,(C_1\phi_k T_{ivc,k+1} + C_2\phi_k + C_3) \tag{20}$$

2. 3. Model of COM The equations governing the physical processes in this model for any cycle contain the state variables and outputs, which are obtained as a functions of model states (X) and input (u) of the previous cycle.

$$X_{k+1} = f(X_{k+1}, u_{i,k}) \tag{21}$$

$$y_k = g(X_k, u_{i,k}), i = 1,2 \tag{22}$$

2. 4. Validation of COM Performance of the COM is validated by transient experimental data extracted using single cylinder Ricardo engine test results [19]. The comparison for two step changes in ϕ and ON are presented. Figures 5 and 6 indicate a comparison of developed model for IMEP, CA50 and test data for 445 cycles.

3. CONTROLLER DESIGN

In the present model, open and closed loop control models are presented. In open loop model single parameter of IMEP is controlled, but in closed loop model both IMEP and CA50 are controlled.

3. 1. Open Loop Control Model In an open loop model, IMEP is controlled by adjusting fuel rate whereas phi is kept constant by adjusting the AFR as shown in Figure 7-a. In this model, more fuel is injected to cylinder according to a base IMEP as initial input.

To avoid changing the equivalence ratio, the AFR is adjusted by a controller. In open loop model equivalence ratio is kept constant to maintain CA50 within operating range. This controller includes two integral feed-forward controllers for IMEP and AFR control.

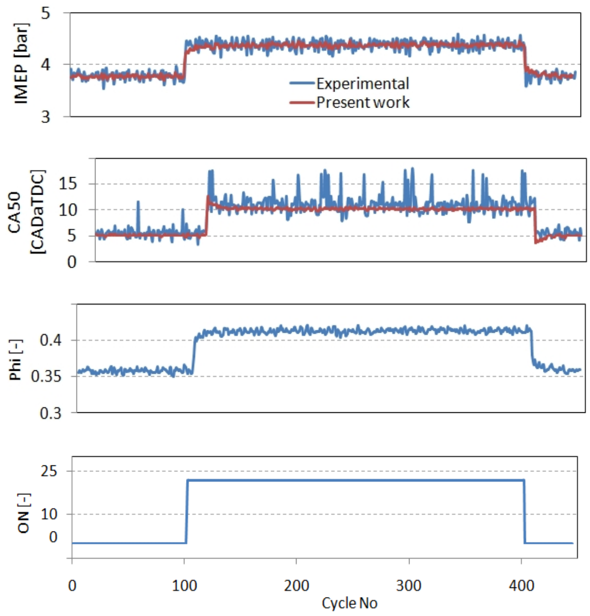

Figure 5. Cycle-to-cycle experimental validation of COM for a step change in ϕ and ON, $P_{man} = 110kPa$, $T_{man} = 91^{\circ}C$, EGR=0%, $P_{exh} = 99kPa$, N=815 rpm.

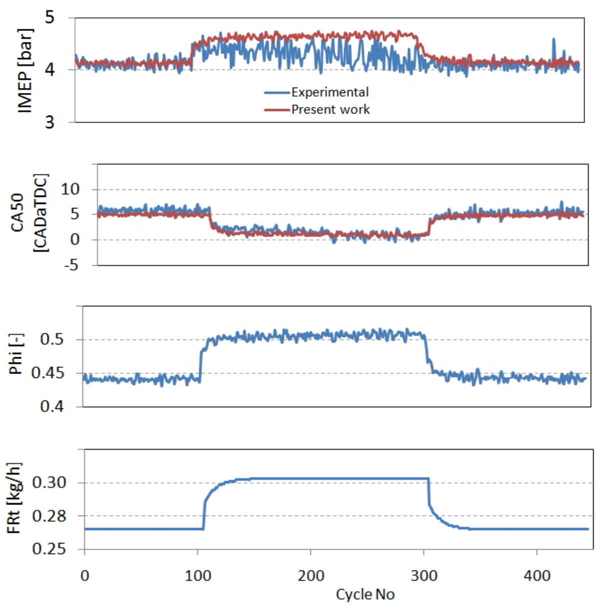

Figure 6. Cycle-to-cycle experimental validation of COM for a step change in ϕ, $P_{man} = 100\,kPa$, $T_{man} = 67^{\circ}C$, EGR=0%, $P_{exh} = 97.3\,kPa$, N=815rpm, ON=0.

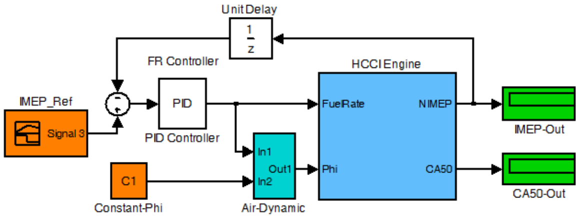

Figure 7(a). Layout of an open loop controller

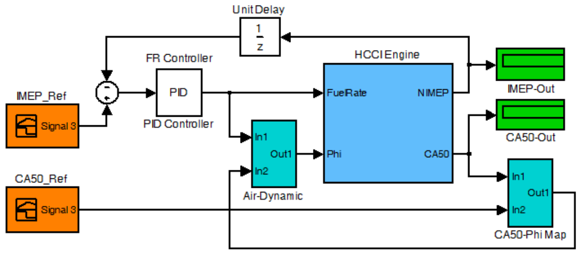

Figure 7(b). Layout of a closed loop controller

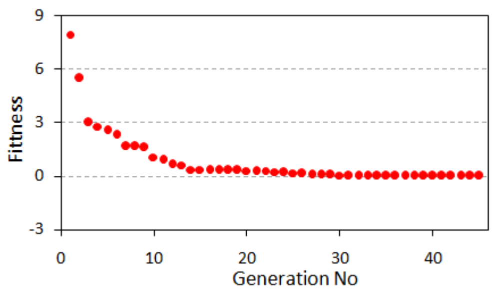

Figure 8. Fitness versus generation number

TABLE 3. The parameters of GA

Parameter	Value
Number of generations	50
Selection Method	Roulette Wheel
Elitism rate	0.02
Crossover type	Arithmetic
Crossover rate	0.8
Mutation rate	0.05

3. 2. Closed Loop Control Model In open loop control model all settings are based on an equivalence ratio, then the combustion phasing cannot be controlled. In order to control the CA50 according to engine operating range an appropriate phi is selected from a CA50-Phi map. The mentioned map should be determined based on other effective parameters such as engine speed, intake manifold temperature and pressure. For any operating point the CA50 is constant then the controller keep phi as constant. When some parameters change for any reason (for instance IMEP demand or disturbances), CA50 for a new operating point varies as well. CA50-Phi map forces the controller to choose proper phi for new operating point and then CA50 error is minimized by a Proportional Integral Derivative (PID) controller that changes by any variation. Figure 7-b shows a closed loop control model that controls IMEP and CA50 at the same time.

3. 3. Tuning PID controller using GA PID controllers are employed in so many industrial automations due to their simplicity, low cost, ease of design and inexpensive maintenance. In this work the PID controller parameters are optimized by Genetic Algorithm (GA). GA are techniques that generate solutions to optimize problems inspired by natural evolution such as inheritance, mutation, selection, and crossover [20]. In this study Matlab Genetic Algorithm Toolbox is used to optimize PID controller parameters. The parameters of GA are shown in Table 3.

The Integral of Absolute Magnitude of the Error (IAE) is chosen as objective function to evaluate fitness of chromosomes:

$$IAE = \int_{\tau_1}^{\tau_2} |e(t)|\, dt \qquad (23)$$

where $e(t)$ is the error signal in time domain.

Figure 8 shows the fitness variation with generation number. It should be noted that generation numbers 1 to 3 are too large to show in the figure; hence, the generation numbers 3 to 50 have been shown. According to this figure, variation from the 25th generation to the next is small. This behavior occurs in deferent generation numbers for different PIDs. This procedure has been done to determine parameters of all PIDs in the controller.

4. RESULTS

In this section, performance of both open and closed loop controllers are studied. Then, the disturbance rejection properties of the controllers are evaluated for step changes in some engine parameters such as intake temperature and engine speed. The model can control the desired work output by considering constraints on air fuel ratio, phi, ensuring that the system stays away from very lean or rich regions to ensure combustion stability. The desired IMEP can be determined by operator then the controller changes the fuel rate so phi varies. In order to control the phi, throttle or air boost pressure controller is used to change the AFR.

4. 1. Tracking Performance Tracking performances of two controllers (open loop and closed loop) are investigated for a positive and negative step changes to meet a desired outputs.

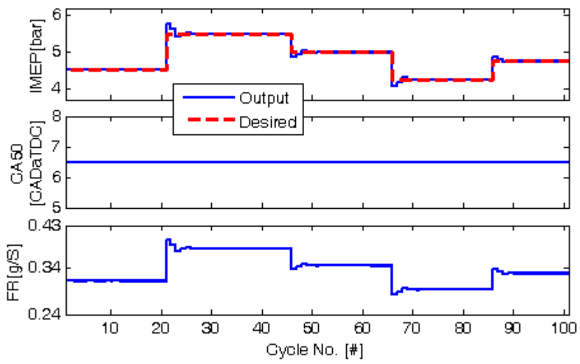

Figure 9. Tracking performance of IMEP controller for constant phi=0.45 (open loop)

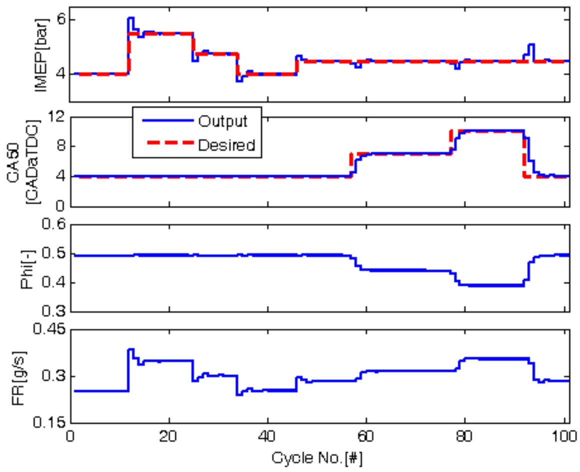

Figure 10. Single tracking performance of IMEP and CA50 controller (closed loop)

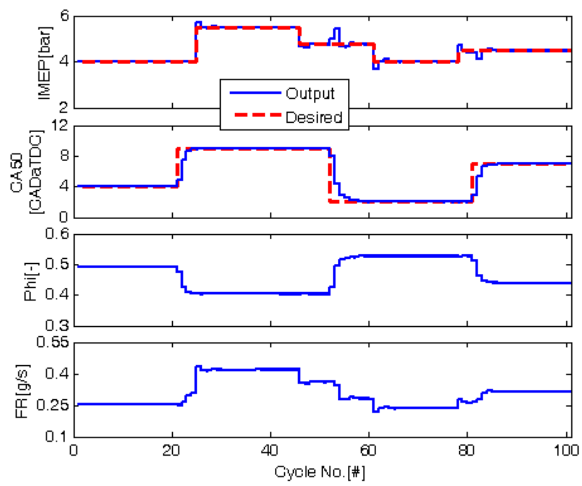

Figure 11. Simultaneous tracking performance of IMEP and CA50 controller (closed loop)

4. 1. 1. Open Loop Controller Tracking performances of open loop controllers are investigated for positive and negative step changes to meet a desired IMEP.

Figure 9 shows the tracking performance results for desired IMEP. CA50 is not controlled and is just the second output of the open loop controller. Results shows that the controller can increase IMEP about 40% in positive step change and can decrease it about 20% in negative step change. Maximum variation of CA50 is less than 4%. In fact, CA50 has a small variation around its operating point because phi is kept constant by adjusting air flow controller.

4. 1. 2. Closed Loop Controller The tracking result when either IMEP or CA50 set-points is changed in a closed loop controller are shown in Figure 10.

The first simulation period within 1 to 50 cycles positive and negative step changes for a desired IMEP evaluate the tracking performance of the IMEP controller. As mentioned before equivalence ratio is kept constant by phi sub-controller then the CA50 variation depends only on IMEP which has less effect on CA50 than phi. In an earlier study phi is used as the main input to control IMEP of the engine [14]. It is obvious that phi variation has disturbance effects on CA50 control and its sub-controller should reject it. In the present work for constant desired CA50, phi remains constant then no overshoot is observed in CA50 control in IMEP variation mode. In the second simulation period for 51 to 100 cycles within positive and negative step changes of desired CA50, evaluation of tracking performance for CA50 controller is carried out. In the CA50 variation mode no overshoot is observed since appropriate phi for CA50 is wisely selected from CA50-phi map.

Results show that the controller can increase IMEP about 40% in positive and can decrease it around 20% in negative step change. Also, CA50 can be increased 100% in positive and negative step change.

In Figure 10 for the closed loop controller there is no steady state error in step change in IMEP and CA50. This behavior is due a PID controller that minimizes the CA50 error after selecting by a phi-CA50 map.

Figure 11 shows the behavior of controller for simultaneous step changes in the desired IMEP and CA50. In fact, this scenario is the best way to evaluate the performance of the controller. For this condition desired IMEP and CA50 increase simultaneously 40% and 100% respectively. Results show that the overshoot for IMEP controller increases in simultaneous step changes is about 12% and is rejected in 3 engine cycles.

The IMEP overshoot is related to the CA50 variations. When CA50 varies in a desired step change its controller select a proper phi to regulate CA50. Phi variations affect on FFR and AFR at the same time. It is obvious that simultaneous changes in phi, FFR and AFR affect the IMEP. On the other hand, no overshoot is observed for CA50 controller despite step changes of

IMEP because controller immediately selects an appropriate phi from CA50-phi map.

Table 4 shows performance analysis for tracking and regulation of the IMEP and CA50 controllers. According to Figure 11, no overshoot and steady state error has been observed in control of CA50. Results show that present controller is capable of tracking both IMEP and CA50 within 4 engine cycles. Controller behavior under these conditions reveals that the engine IMEP can be controlled for any variation of CA50.

4. 2. Disturbance Rejection Performance

Variations in engine speed and intake temperature as disturbances are used to investigate the performance of closed loop controller. The constant optimum set point has been selected by using the experimental data [4]. Figures 12 and 13 show the performance of positive and negative step disturbances rejection of the controller.

TABLE 4. Tracking performance analysis for IMEP and CA50 controller

Performance	CA50 Sub-controller	IMEP Sub-controller
Rise Time	1 cycle	1 cycle
Max. Overshoot	0	0.46 bar
Steady State Error	0 CAD	0 bar
Cycles for Regulation	2 cycle	4 cycle

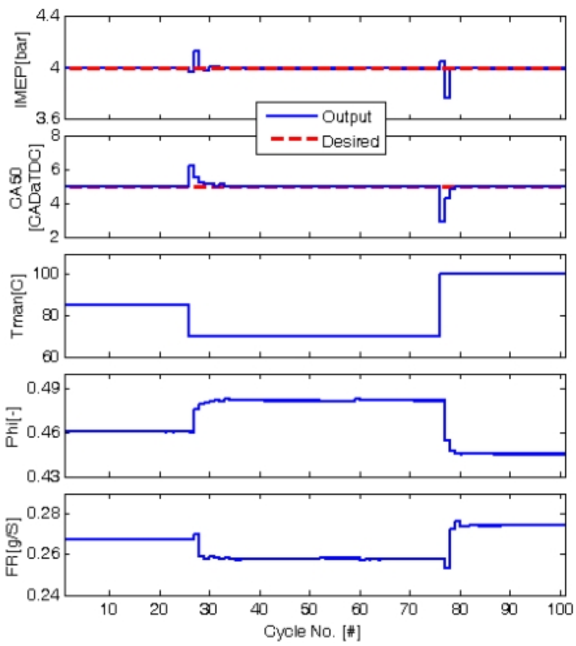

Figure 12. Disturbance rejection for intake temperature step changes (85 - 70 - 100 C)

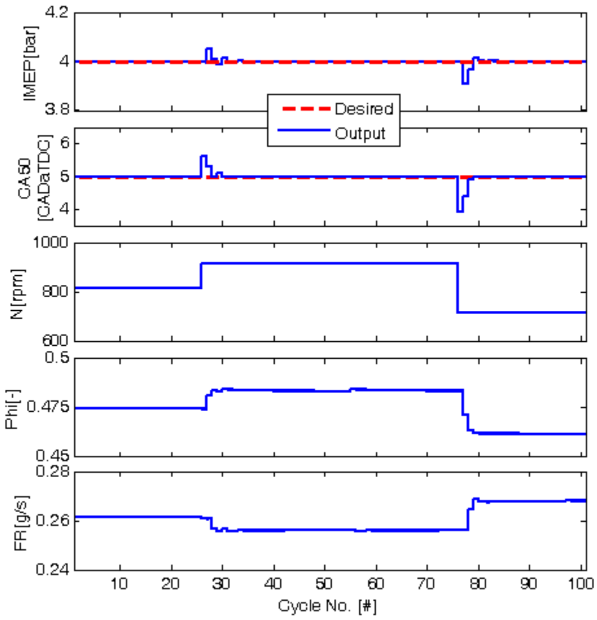

Figure 13. Disturbance rejection: engine speed step changes (820 –920 -720 rpm)

TABLE 5. Performance of disturbance rejection of IMEP and CA50 controller

Disturbance	Control output	Max. absolute deviation	Rejection speed [cycle]
T_{man}	IMEP[bar]	0.15	2
	CA50 [aTDC]	1.15	3
Speed	IMEP[bar]	0.5	2
	CA50 [aTDC]	1.1	3

Figures 12 and 13 show that for engine speed step change fuel rate remains constant but for intake temperature variations fuel rate decreases. Because of IMEP depends on both fuel rate and intake temperature; therefore, engine speed has no effect on IMEP. On the other hand, engine speed affects CA50 much more than intake temperature. Figures 12 and 13 explain how Controller compensates the effect of two mentioned disturbances by means of phi variations. When intake charge temperature decreases CA50 retards to compensate a fixed level, phi should be increases. Also, CA50 retards when engine speed increases consequently phi increase to overcome the engine speed effect.

Table 5 shows maximum deviations from set value and number of engine cycles needed to minimize the output. According to two disturbance conditions tested in Figures 12 and 13, the present model-based controller can stabilize the output within 2-3 engine cycles. Maximum deviation is about 0.5 and 1.15 for IMEP and CA50, respectively.

5. CONCLUSION

In present work a single zone thermodynamic model and a COM was developed to predict the performance of cycle-to-cycle in an HCCI engine. The COM is setup with some correlations such as IMEP and SOC prediction which models the physical behavior of a HCCI engine. These correlations are obtained by engine test data or HCCI thermodynamic model. It can be claimed that present method is suitable for control HCCI engine. The mentioned model was validated with the HCCI test data at steady state and transient operating conditions. An IMEP predicting model has been presented and validated by test data. According to this model IMEP strongly depends on FFR. FFR is the main parameter to control the engine work output. In present control model FFR and AFR vary simultaneously to increase IMEP like a fuel injection system in conventional CI engine. FFR and AFR change such that the phi remains constant. The COM uses three controllers FFR, AFR and CA50 controller to control IMEP and CA50 as outputs. Two main inputs are FFR and phi and AFR is the third input that control IMEP and phi at the same time. In order to precisely control CA50, appropriate phi is selected from a CA50-Phi map which is developed for a set of different engine operating conditions. Results show that the controller can track desired cycle-to-cycle IMEP and CA50. The mentioned controller is a model-based engine controller with a feed-forward integral controller. No overshoot was observed in mode control of CA50 and IMEP variations. Performance of the controller was also evaluated under physical disturbances such as engine speed and intake manifold temperature step changes. The results show that the controller can reject these disturbances in 2 to 3 engine cycles, while maintaining deviations within 1.15 CAD and 0.5 bar.

6. ACKNOWLEDGEMENTS

The authors express their deep appreciation to Professor Bob Koch from the University of Alberta for providing the experimental data used to validate the COM in this study.

7. REFERENCES

1. Boussouara, K., Merabet, A. and Kadja, M., "Modeling of combustion and carbon oxides formation in direct injection diesel engine", ***International Journal of Engineering***, Vol. 25, No. 3, (2012), 211-219.
2. Khalilarya, S., Jafarmadar, S. and Nemati, A., "Hydrogen and ethanol as potential alternative fuels compared to gasoline under improved exhaust gas recirculation", ***International Journal of Engineering***, Vol. 27, No. 3, (2014)., 449-459
3. Zhao, H., "Homogeneous charge compression ignition (HCCI) and controlled auto ignition (CAI) engines for the automotive industry", ***Woodhead, Brunel University, UK***, (2007).
4. Shahbakhti, M. and Koch, C., "Characterizing the cyclic variability of ignition timing in a homogeneous charge compression ignition engine fuelled with n-heptane/iso-octane blend fuels", ***International Journal of Engine Research***, Vol. 9, No. 5, (2008), 361-397.
5. Nazoktabar, M., Jazayeri, S., Jahanian, O. and Shahbakhti, M., "Using a single zone thermodynamic model in an hcci engine to predict effective controlling parameters", ***The Journal of Engine Research***, Vol. 25, (2013), 13-23.
6. Shahbakhti, M., Lupul, R. and Koch, C.R., "Cyclic variations of ignition timing in an hcci engine", in ASME/IEEE 2007 Joint Rail Conference and Internal Combustion Engine Division Spring Technical Conference, American Society of Mechanical Engineers., (2007), 405-415.
7. Shaver, G.M., Gerdes, J.C. and Roelle, M.J., "Physics-based modeling and control of residual-affected hcci engines", ***Journal of Dynamic Systems, Measurement, and Control***, Vol. 131, No. 2, (2009),
8. Widd, A., Ekholm, K., Tunestal, P. and Johansson, R., "Physics-based model predictive control of hcci combustion phasing using fast thermal management and vva", ***Control Systems Technology, IEEE Transactions on***, Vol. 20, No. 3, (2012), 688-699.
9. Ravi, N., Roelle, M.J., Liao, H.-H., Jungkunz, A.F., Chang, C.-F., Park, S. and Gerdes, J.C., "Model-based control of HCCI engines using exhaust recompression", ***Control Systems Technology, IEEE Transactions on***, Vol. 18, No. 6, (2010), 1289-1302.
10. Audet, A. and Koch, C.R., Actuator comparison for closed loop control of hccic combustion timing. (2009), SAE Technical Paper.
11. Bidarvatan, M., Shahbakhti, M. and Jazayeri, S.A., Model-based control of combustion phasing in an hcci engine. (2012), SAE Technical Paper.
12. Ravi, N., Liao, H.-H., Jungkunz, A.F., Widd, A. and Gerdes, J.C., "Model predictive control of hcci using variable valve actuation and fuel injection", ***Control Engineering Practice***, Vol. 20, No. 4, (2012), 421-430.
13. Ravi, N., Liao, H.-H., Jungkunz, A.F., Chang, C.-F., Song, H.H. and Gerdes, J.C., "Modeling and control of an exhaust recompression HCCI engine using split injection", ***Journal of Dynamic Systems, Measurement, and Control***, Vol. 134, No. 1, (2012)
14. Bidarvatan, M. and Shahbakhti, M., Two-input two-output control of blended fuel hcci engines. (2013), SAE Technical Paper.
15. Heywood, J.B., "Internal combustion engine fundamentals, Mcgraw-hill New York, Vol. 930, (1988).
16. Kirchen, P., Shahbakhti, M. and Koch, C.R., "A skeletal kinetic mechanism for prf combustion in hcci engines", ***Combustion Science and Technology***, Vol. 179, No. 6, (2007), 1059-1083.
17. Nobakht, A.Y., Saray, R.K. and Astiar, G.S., "Optimization of gri-mech 3.0 mechanism using hcci combustion models and genetic algorithm", ***International Journal of Engineering, Transactions A: Basics***, Vol. 24, No. 2, (2011), 155-168.
18. Jafarmadar S. and Javani N., "Exergy analysis of natural gas/dme combustion in homogeneous charge compression ignition engines (HCCI) using zero-dimensional model with detailed chemical kinetics mechanism", [in press], ***International Journal Exergy***, (2013).
19. Shahbakhti, M. and Koch, C.R., Dynamic modeling of hcci combustion timing in transient fueling operation. (2009), SAE Technical Paper.

20. Holland, J.H., "Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence, U Michigan Press, (1975).

Controlling the Power Output and Combustion Phasing in an HCCI Engine

M. Nazoktabar, S. A. Jazayeri

Mechanical Engineering Department, K.N. Toosi University of Technology, Tehran, Iran

PAPER INFO

Paper history:
Received 15 May 2014
Received in revised form 16 June 2014
Accepted 26 June 2014

Keywords:
HCCI Engine Control
Two Input Two Output Controller
Fuel Rate & Phi Inputs
IMEP & CA50 Outputs

چکیده

یکی از چالش‌های عمده در توسعه موتورهای اشتعال تراکمی کنترل هم‌زمان زمان‌بندی احتراق (CA50) و فشار متوسط موثر اندیکاتوری (IMEP) یا توان موتور می‌باشد. در کار حاضر راهبرد جدیدی در کنترل این دو پارامتر برای شرایط کارکردی مختلف موتور ارایه شده است. در آغاز یک مدل ترموسینتیک تک‌ناحیه‌ای با مکانیزم مفصل شیمیایی سوخت PRF برای پیش‌بینی زمان آغاز احتراق، IMEP و پارامترهای ویژه ترمودینامیکی توسعه داده شده است. پس از آن یک مدل کنترلی برای پیش‌بینی CA50 و IMEP در هر سیکل موتور ارایه شده است. مدل کنترلی با داده‌های آزمون موتور ریکاردو در شرایط گذرا صحه‌گذاری و در نهایت هم یک کنترلر که قابلیت کنترل CA50 و IMEP را دارد طراحی شده است. در این کار دو کنترلر مدارباز و مداربسته ارایه می‌شود. کارایی کنترلر با کمک یک مدل فیزیکی برای ارزیابی عملکرد آن و توانایی در حذف اغتشاشات بررسی شده است. نتایج نشان می‌دهند که کنترلر طراحی شده قابلیت کنترل دو پارامتر CA50 و IMEP و همچنین حذف اغتشاشات ناشی از تغییر در دور موتور و دمای ورروودی را دارد.

doi: *10.5829/idosi.ije.2014.27.11b.14*